Renewable and Sustainable Energy Reviews 29 (2014) 316–324

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Comparison of energy consumption and GHG emissions of open field and greenhouse strawberry production

Benyamin Khoshnevisan, Hanifreza Motamed Shariati, Shahin Rafiee *, Hossein Mousazadeh

Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran

ARTICLE INFO

Article history:
Received 24 January 2013
Received in revised form
25 August 2013
Accepted 26 August 2013
Available online 20 September 2013

Keywords:
Strawberry
Energy
Data envelopment analysis
GHG emission

ABSTRACT

The greenhouse areas in Iran have expanded rapidly and the greenhouse holders have shown a great tendency to cultivation of those crops that used to be cultivated in open fields. Although, greenhouses are intensive in terms of yield and whole year production, they are considered being one of the major contributors to greenhouse gases (GHG) emissions in the agricultural sector. In the present study strawberry cultivation in greenhouses (GH) and open fields (OF) was selected as a representative of those crops which can be grown in both systems. Initial data were randomly collected from 70 OFs and 33 GHs in province of Gilan, Iran. Energy consumption and GHG emission of two different strawberry production systems were compared. Moreover, energy use efficiency of GH producers due to more energy consumption was studied, then degrees of technical efficiency (TE), pure technical efficiency (PTE) and scale efficiency (SE) were determined using data envelopment analysis (DEA). Additionally, the amount of energy inputs wasted in inefficient greenhouses was assessed and energy saving was computed. Furthermore, the effect of energy optimization on GHG emission was investigated and the total amount of GHG emission was calculated. The total average of energy input and output was estimated at 35,092.4 MJ ha^{-1} and 10,405.9 MJ ha^{-1} for OF production and, similarly, 1,356,932.8 MJ ha^{-1} and 137,772.4 MJ ha^{-1} for GH strawberry production. Total GHG emission was calculated as 803.4 kg CO_{2eq} ha^{-1} and 35083.5 kg CO_{2eq} ha^{-1} for OF and GH production, respectively. Based on the evaluations 20.2% (273,902.8 MJ ha^{-1}) of overall energy sources can be saved if the performance of inefficient farmers is enhanced. Optimizing energy in the greenhouse production can result in a significant reduction in total GHG emission and the present emission of GHG can be reduced to the value of 29309.1 kg CO_{2eq} ha^{-1}.

Contents

* Corresponding author. Tel.: +98 2632801011; fax: +98 2632808138.
E-mail addresses: b_khoshnevisan@ut.ac.ir (B. Khoshnevisan), hr_motamed@ut.ac.ir (H.M. Shariati), shahinrafiee@ut.ac.ir (S. Rafiee).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.08.098

1. Introduction

Intensive agriculture is meant to achieve maximum production with the minimum cropping surface, as in the case of greenhouse cultivation. In recent years, the area covered by intensive cropping systems has been expanded (plastic mulch, plastic tunnels and plastic greenhouses) in response to the demand of developed countries for year-round fresh products [1]. An agricultural greenhouse consists of frames of either metallic or wooden structure covered with a transparent material in which crops are grown under favorable and controlled environmental conditions. Open field agricultural practices have no control on the environment parameters such as sunlight, air composition and temperature that affect the plant growth. Hence, a large number of winter vegetables, flowers and other horticultural crops have to be transported from distant places [2].

In the period of 2002–2007, greenhouse areas of Iran were expanded from 3380 ha to 6630 ha including an increasing rate of 96%. The shares of greenhouse crops production were as follows: vegetables 59.3%, flowers 39.81%, fruits 0.54% and mushroom 0.35% [3]. In recent years, strawberry production has drawn the attention of the most greenhouse holders due to its gross value of production and nutrient value [4]. In Iran, strawberry is widely cultivated in the open fields in some provinces such as Kurdistan and Gilan and also it is grown in greenhouses in some other regions. Some of these areas are appropriate for open field strawberry production, but greenhouse holders of these areas show tendency to grow this crop in their greenhouses. Greenhouses are considered as intensive farming system from productive point of view; however they are the most important energy consumers in the agricultural sector. More energy consumption causes numerous environmental problems of which global warming and greenhouse gases (GHG) are regarded as the most important ones.

Energy is a fundamental component in the process of economic development, as it provides imperative services that maintain economic activities and the quality of human life. Thus, shortages of energy are a serious constraint on the development of low income countries [5]. Increase in the use of energy inputs in agriculture has led to numerous environmental problems like high consumption of non-renewable energy resources, loss of biodiversity, pollution of the aquatic environment by the nutrients nitrogen and phosphorus as well as pesticides [6]. Energy input–output analyses are usually applied to investigate the energy use efficiency and determine the environmental facets of inefficient energy consumption. Several studies have been conducted on energy use in open field and greenhouse production [3,5,7–12], whereas, a few studies have been published on energy analysis and GHG emission of agricultural crops [13].

Therefore, this study was conducted with the following objectives: (a) to estimate energy consumption in open field and greenhouse strawberry production; (b) to compare energy ratio and other energy indices of these two different systems; (c) to assess GHG emission of open field and greenhouse strawberry cultivation and (d) to find some solutions to reduce waste of energy and GHG emission in the inefficient systems.

2. Materials and methods

2.1. Data collection and processing

The present study was carried out in province of Gilan, Iran. Data were collected from rural areas of Rasht (The capital of Gilan province; a province in the north of Iran next to the Caspian Sea) in 2011/2012 production year. The annual average rainfall in above-mentioned area is almost 1100 mm. The soil analysis illustrated that the structure of soil was clay and clay loam. The reason for selecting this area was to investigate whether either of the cultivation systems; open field or greenhouse strawberry production, was reasonable from energy consumption and GHG emission point of views.

The sample size was determined using Cochran technique [5]. Based on this sampling method, 70 open field owners and 33 greenhouse holders were chosen and inquired using face-to-face questionnaire method.

Energy inputs for strawberry production included human labor, chemical fertilizers, farmyard manure (FYM), diesel fuel, electricity, natural gas, biocides, machinery and water for irrigation. In other words, the same energy inputs with different application rates were used in both open-field and greenhouse production except natural gas which is only used in greenhouses by heating system. For both systems, the amount of produced strawberry was considered as output energy. In agricultural production such as greenhouse strawberry production the produced crops are the main outputs of the production process. Produced crops contain protein, carbohydrate, and fat considered as sources of energy for human beings. Therefore, the term output energy is widely used for the outputs of agricultural production. For instance lemon contains 14.1 kJ/g protein, 35 kJ/g fat, and 10.4 kJ/g carbohydrate. Energy equivalents of inputs and outputs were exercised to assess the total energy input and output.

One of the problems of this methodology of energy analysis is unifying criteria for assigning amounts of energy to each input. The lack of reliable data for each country or region forces the researcher, in many cases, to take values from other countries for which circumstances are different. But this problem is not crucial when the comparison is made within the same region and for a specific region they can be merely applied to allow the possibility of comparing different farms from energy consumption point of view. The conversion factor of each input material was estimated based on the amount of energy which was used during manufacturing process. For instance, the production and the repair of farm machinery are important issues in the total energy balance. Accordingly, several steps should be included in calculating this energy. First, the energy used in producing the raw materials (like steel, 22–60 MJ/kg); second, the quantity of energy required in the manufacturing process (mean value of these two first steps, 87 MJ/kg); third, the transportation of the machine to the consumer (estimated, 8.8 MJ/kg); and fourth, the energy sequestered in repairs. Due to the fact that the calculation of these factors is beyond the scope of the present study, these conversion factors were extracted from previous studies and are summarized in Table 1.

The amount of rainfall in the studied region is high, so rainfall can provide some parts of plants' water need in OF production and the rest is provided by agricultural wells. Water for irrigation was extracted from agricultural well by electrical pumps. Energy needed for pumping water was calculated as Eq. (1) [14]:

$$\mathrm{DE} = \frac{\gamma \mathrm{gHQ}}{\varepsilon_{\mathrm{p}}\varepsilon_q} \tag{1}$$

where 'DE' presents direct energy (J/ha), 'g' is acceleration due to gravity (ms^{-2}), 'H' is total dynamic head (m), 'Q' is volume of required water for one cultivating season (m^3 ha^{-1}), 'γ' is density of water (kg m^{-3}), 'ε_p' is electrical pump efficiency (44% calculated) and 'ε_q' is total power conversion efficiency (18–20%) [5,14].

The energy ratio can be used to illustrate the relationship between energy inputs and output. A rise in the energy ratio indicates improvement in energy efficiency with good environmental performance and vice versa [15]. By employing the energy equivalents of inputs and output (Table 1) energy indices – the energy ratio (energy use efficiency), energy productivity, specific

Table 1
Energy coefficients of different inputs and outputs used.

Inputs	Unit	Energy coefficients (MJ unit^{-1})	Reference
A. Inputs			
1. Machinery			
Tractor and self-propelled	kg yr[a]	9–10	[13]
Stationary equipment	kg yr[a]	8–10	[13]
Implement and machinery	kg yr[a]	6–8	[13]
2. Human labor	h	1.96	[14]
3. Natural gas	m^3	49.5	[14]
4. Diesel fuel	L	47.8	[14]
5. Biocide			
Herbicide	kg	85	[13]
Fungicide	kg	295	[13]
Insecticide	kg	115	[13]
6. Fertilizers			
Nitrogen (N)	kg	66.14	[4]
Phosphate (P_2O_5)	kg	12.44	[4]
Potassium (K_2O)	kg	11.15	[4]
Micro	kg	120	[4]
7. FYM	kg	0.3	[13]
8. Water for irrigation	m^3	1.02	[3]
9. Electricity	kWh	12	[14]
B. Out put			
1. Strawberry	kg	0.8	[4]

[a] The economic life of machine (year).

Table 2
Greenhouse gas (GHG) emission coefficients of agricultural inputs.

Inputs	Unit	GHG coefficient[a]	Reference
Machinery	MJ	0.071	[13]
Diesel fuel	L	2.76	[13]
Chemical fertilizers			
(a) Nitrogen (N)	kg	1.3	[17]
(b) Phosphate (P_2O_5)	kg	0.2	[17]
(c) Potassium (K_2O)	kg	0.2	[17]
Biocide			
(a) Herbicide	kg	6.3	[17]
(b) Insecticide	kg	5.1	[17]
(c) Fungicide	kg	3.9	[17]
Natural gas	m^3	0.85	[17]
Electricity [b]	kWh	0.608	[13]

[a] kg CO_2 eq. unit^{-1}.
[b] The power plant burns LNG.

energy and net energy – were calculated [9,16]:

$$\text{Energy use efficiency} = \text{output energy (MJ ha}^{-1}\text{)/input energy (MJ ha}^{-1}\text{)} \quad (2)$$

$$\text{Energy productivity} = \text{potato output (kg ha}^{-1}\text{)/input energy (MJ ha}^{-1}\text{)} \quad (3)$$

$$\text{Specific energy} = \text{input energy (MJ ha}^{-1}\text{)/strawberry output (kg ha}^{-1}\text{)} \quad (4)$$

$$\text{Net energy} = \text{output energy(MJ ha}^{-1}\text{)} - \text{input energy (MJ ha}^{-1}\text{)} \quad (5)$$

To have a clear vision of different forms of energy, energy demand in agriculture can be divided into direct (DE) and indirect (IDE), renewable (RE) and non-renewable (NRE) energies. In the current study human labor, diesel fuel, electricity, natural gas and water for irrigation were considered as DE while FYM, chemical fertilizer, biocides and machinery were regarded as IDE sources. RE consisted of human labor, FYM and water for irrigation; and NRE sources included electricity, natural gas, machinery, diesel fuel, biocides, and chemical fertilizers.

2.2. GHG emission

Agricultural production necessitates employing a multitude of input materials (fertilizers, biocides, seeds, etc.) and energy carriers (natural gas, diesel fuel, etc.). Production, formulation, storage, distribution of agricultural inputs and their applications with agricultural machinery lead to combustion of fossil fuel, and use of energy from alternate sources which emit CO_2 and other greenhouse gases (GHGs) into the atmosphere [17]. To quantify the GHG emissions of strawberry production, carbon emission coefficients of agricultural inputs were applied. GHG emission coefficients are depicted in Table 2. GHG emissions were worked out by multiplying the input application rate (diesel fuel, chemical fertilizers, machinery, pesticides, electricity and natural gas) by its corresponding emission coefficient. To calculate the GHG emission of energy inputs gives an opportunity to compare various production systems regarding the environmental problems.

In order to compare the amount of GHG emission from open field strawberry production with that of greenhouse production GHG ratio was proposed to be calculated as following:

$$\text{GHG ratio} = \frac{\text{Total GHG emission (kg CO}_{2\text{eq}}\text{ ha}^{-1}\text{)}}{\text{Strawberry output } (t\text{ ha}^{-1})} \quad (6)$$

2.3. Data envelopment analysis

In this study, data envelopment analysis (DEA) methodology was applied to determine efficiency degree of strawberry producers in order to calculate the amount of energy saving and GHG emission reduction. Input variables were considered based on energy per hectare (MJ ha^{-1}) and strawberry yield (kg ha^{-1}) was chosen as output variable.

DEA is a multi-factor productivity analysis model for measuring the relative efficiencies of a homogenous set of decision making units (DMUs). The efficiency score in the presence of multiple input and output factors is defined as [18]:

$$\text{Efficiency} = \frac{\text{weighted sum of outputs}}{\text{weighted sum of inputs}} \quad (7)$$

Assuming that there are n DMUs, each with m inputs and s outputs, the relative efficiency score of a test DMU p is obtained by solving the following model proposed by Charnes and Cooper [19]:

$$\max h_k = \frac{\sum_{r=1}^{s} u_{rk} y_{rk}}{\sum_{i=1}^{m} v_{ik} x_{ik}} \quad (8)$$

subject to

$$\frac{\sum_{r=1}^{s} u_{rk} y_{rj}}{\sum_{i=1}^{m} v_{ik} x_{ij}} \le 1; \ j = 1, \ldots, n$$

$$u_{rk}, v_{ik} \ge 0; \ r = 1, \ldots, s; \ i = 1, \ldots, m$$

where 'k' is the DMU being evaluated in the set of j=1,2,…,n DMUs; 'h_k' the measure of efficiency of DMU 'k', the (DMU) in the set of j=1,2,…,n (DMU)s rated relatively to the others; 'y_{rk}' the amount of output 'r' produced by DMU 'k' during the period of observation; 'x_{ik}' the amount of resource input 'i' used by DMU 'k' during the period of observation; 'y_{rj}' the amount of service output 'r' produced by DMU 'j' during the period of observation; 'x_{ij}' the amount of resource input 'i' used by DMU 'j' during the period of observation; 'u_{rk}' the weight assigned to service output 'r' computed in the solution to the DEA model; 'v_{ik}' the weight assigned to resource

of input 'i' computed in the solution to the DEA model; 'm' the number of inputs used by the DMUs; and 's' the number of outputs produced by the DMUs [20].

Two basic DEA models are Charnes Cooper Rhodes (CCR) model and Banker Charnes Cooper (BCC) model. These models can be distinguished by the envelopment surface and the orientation. CCR and BCC models were employed in the present study. CCR model which was built on the assumption of constant returns to scale (CRS), was suggested by Charnes and Cooper [19]. Later, Banker and Charnes [21] introduced the BCC model based on variable returns to scale (VRS) and it was also called as local efficiency model. The models with CRS envelopment surface assume that an increase in inputs will result in a proportional increase in outputs. The VRS model allows an increase in input values to result in a non-proportional increase of output levels. The VRS surface envelops the population by connecting the outermost DMUs, including the one approached by the CRS surface. Hence the BCC model envelops more data and efficiency scores are bigger than or equal to those of CCR.

DEA models are broadly divided into two categories on the basis of orientation: input-oriented and output-oriented. Input-oriented models have the objective of minimizing inputs while maintaining the same level of outputs, whereas output-oriented models focus on increasing outputs with the same level of inputs [22]. Due to the fact that in agricultural systems, farmers can control the application rate of input materials while they have no direct control over outputs, in this study an input oriented DEA model was used to determine efficient and inefficient DMUs.

Three different forms of efficiency are defined by DEA; technical efficiency (TE), pure technical efficiency (PTE) and scale efficiency (SE). TE is defined as the DMU's ability to achieve maximum output from given inputs or alternatively, to achieve maximum feasible reductions in input quantities given input prices and output [22]. Inappropriate operation and inadequate scale of a farm are two main reasons for inefficiency of a DMU. CCR model includes both TE and SE while BCC model calculates only PTE of DMUs. In order to obtain SE in the present study, both CCR and BCC models were calculated and SE was defined as follows: [23]:

$$SE = \frac{\theta_{CCR}}{\theta_{BCC}} \tag{9}$$

where 'θ_{CCR}' and 'θ_{BCC}' are the CCR and BCC scores of a DMU, respectively. $SE=1$ shows scale efficiency (or CRS) and $SE<1$ indicates scale inefficiency.

Also, in order to assess the efficiency indices of greenhouses, the DEA software Efficiency Measurement Systems (EMS), Version 1.3, was applied. Using EMS software three models including CCR, BCC and non-increasing returns to scale (NIRS) were built. To find the most appropriate (efficient) DMUs, they should be ranked according to their importance for inefficient units which do not lie on the efficient frontier. The benchmark ranking method is the most prevalent technique in DEA studies; therefore it was used in the present study. The number of times each efficient DMU was observed in a referent set was given by software meaning that the efficient DMUs are similar to the output and input levels of inefficient DMUs. Efficient DMUs which are repeated more frequently in the referent set are considered superior and obtain a higher rank.

3. Results and discussions

3.1. Energy use pattern

Table 3 summarizes energy equivalents of GH and OF strawberry production. As it can be seen the total input energy was calculated as 35,092.4 MJ ha^{-1} and 1,356,932.8 MJ ha^{-1}, for OF and GH production, respectively. Among the input energies, nitrogen with a share of 41% was the most energy consumer in OF production followed by human labor (16%) and biocides (9%). The high labor energy in contrast to low machinery energy in OF strawberry production disclosed that strawberry production relied on human labors to be cultivated in the studied area which is not highly mechanized. Due to a lack of more similar studies on OF strawberry production the results were compared with other crops. In a research on energy consumption and CO_2 emissions analysis of potato production, Pishgar-Komleh et al. [13] showed that nitrogen with a share of 40%, held the first rank among all input energies. In another study on determination and modeling of energy consumption in wheat production, Safa and Samarasinghe [24] demonstrated that the chemical fertilizer was the most important energy consumer. Similar results were gained by other researchers [25,26].

Table 3
Energy input–output in various operations.

Inputs/output	Open field strawberry		Greenhouse strawberry	
	Total energy equivalent (MJ ha^{-1})	Percentage	Total energy equivalent (MJ ha^{-1})	Percentage
A. Input				
1. Human labor	5748.0	16	25134.3	1.85
2. Chemical fertilizer				
N	14313.3	41	44654.5	3.29
P_2O_5	2488.1	7	25196.7	1.86
K_2O	2719.8	8	11707.5	0.86
Micro	–	–	22509.1	1.66
3. FYM	1623.1	5	19454.5	1.43
4. Biocides	3166.9	9	12785.3	0.41
5. Machinery	1121.8	3	1154.5	0.09
6. Water for irrigation	1011.3	3	24353.3	1.79
7. Diesel fuel	1354.4	4	12785.3	0.94
8. Electricity	1545.6	4	372068.4	27.42
9. Natural gas	–	–	792392.9	58.4
Total input energy	35092.4	100	1356932.8	100
B. Output				
Strawberry	10405.9		137772.4	

The percentage distribution of energy in GH production revealed that natural gas had the highest amount followed by electricity. The majority of natural gas and electricity were used for heaters and drop irrigation systems (electrical pumps). Banaeian and Omid [4] in their studies on energy and economic analysis of greenhouse strawberry production showed that the share of diesel fuel and electricity from the total energy input were the highest as 78% and 4.55%. They mentioned that diesel fuel was mostly used for heating systems. In other studies on energy input–output analysis of greenhouse production, heaters and irrigation system were introduced as the most energy consumer [3,8,10]. As it was observed, heating system and electrical pump in greenhouses located in Iran consume a great deal of natural gas and electricity. It necessitates finding solutions to reduce the consumption of these energy sources, because apart from the depletion of fossil fuels they cause irreversible damage on the environment.

The rainfall and the water well were two main sources of water for OF strawberry production while water well was considered as the only source of water for greenhouses. Accordingly, electrical motors are applied to extract water, therefore, the electricity was mostly consumed for water extraction (heating systems also consume electricity). Hence, the major difference between the two cultivation systems from electricity energy point of view was due to the above-mentioned reasons.

Apart from natural gas and electricity, the consumption of chemical fertilizers in GH production was so high. Chemical fertilizers

were the third demanding energy input for greenhouse strawberry production with 104,067.8 MJ ha^{-1}, which was 5.3 times more than fertilizer energy for OF strawberry production.

Based on the evaluations, the amount of labor energy for GH production was more than its amount for OF production. It was due to the fact that the yield of strawberry in GH is higher than that of OF, therefore GH production needed more human labor for harvesting operation. The average strawberry yield in OF production system was 5.4 t ha^{-1} while it was about 72.5 t ha^{-1} in GH production. The high yield of GH strawberry production was achieved due to environmental controlled conditions. The greenhouse structure and intensive use of fertilizers and chemicals increase the crop cycle and lead to an increase in the yield. Except for field preparation other agricultural operations in both systems were carried out by human labor due to lack of mechanization.

According to the results of Table 3, the total output energy in GH production was significantly higher than that of the other system. Energy ratio, energy productivity, specific energy and net energy can be seen in Table 4. Also, energy from different sources was classified as direct–indirect and renewable–nonrenewable forms. The results showed that the energy ratio in OF production was higher than its amount in the GH. The average value of energy ratio was estimated at 0.3 for OF strawberry cultivation, while it was calculated as 0.12 for GH production. Banaeian and Omid [4] reported that the energy ratio of strawberry production in Tehran province was 0.15. The energy ratio of four major greenhouse vegetables – tomato, pepper, cucumber and eggplant – was reported as 0.32, 0.19, 0.31, 0.23, respectively [11]. The results of energy ratio calculated in the present study along with the results concluded by previous studies disclose that a high quantity of energy consumption is consumed in all greenhouses in Iran.

Net energy for both production systems in this region was negative and it revealed that energy consumption was so high especially for GH production. Either by making a reduction in input energies or an increase in yield using the same or lower input energies, the amount of net energy can be modified. In terms of greenhouse production, changing the traditional structure of greenhouses can be the first step to save energy. Low level technology of ventilation was accounted as the second major problem. In order to eliminate this problem, efficient (high technology) heating systems and thermostat controller should be applied.

The results of Table 4 and Fig. 1 indicated that direct–indirect and renewable–nonrenewable energy resources were significantly different. As can be seen in Fig. 1 the share of NRE in both systems is so high. Among the DE and NRE sources natural gas and electricity were accounted as the most influential factors, so, a considerable attention on energy management should be drawn.

Table 4
Energy indices and different forms of energy in strawberry production.

Item	Unit	Open field	Greenhouse
Energy ratio	–––	0.30	0.12
Energy productivity	kg MJ^{-1}	0.16	0.06
Specific energy	MJ kg^{-1}	6.71	20.39
Net energy	MJ ha^{-1}	−24686.5	−1219920.17
Direct energy [a]	MJ ha^{-1}	9659.3	1226734.1
Indirect energy [b]	MJ ha^{-1}	25433.0	130198.8
Renewable energy [c]	MJ ha^{-1}	8382.4	68942.1
Non-renewable energy [d]	MJ ha^{-1}	26710.0	1287990.8
Total energy	MJ ha^{-1}	35092.4	1356932.8

[a] Include human labor, diesel fuel, electricity, natural gas and water for irrigation.
[b] Include machinery, biocide, FYM and chemical fertilizer.
[c] Include human labor, FYM and water for irrigation.
[d] Include machinery, chemical fertilizer, electricity, natural gas and diesel fuel.

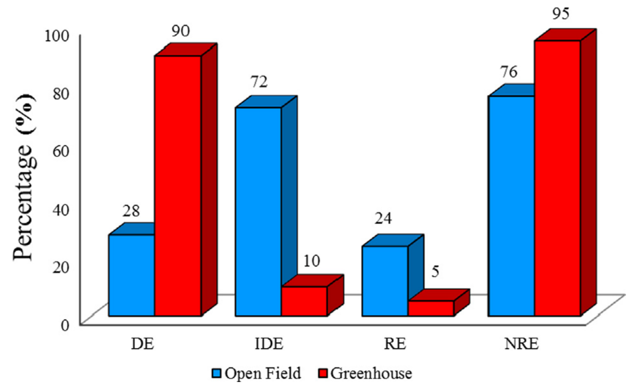

Fig. 1. The share of total mean energy inputs as direct (DE), indirect (IDE), renewable (RE) and non-renewable (NRE) forms.

Table 5
Greenhouse gas emissions of inputs in strawberry production.

Item	OF production		GH production	
	GHG emission (kg $CO_{2eq.}$ ha^{-1})	Percentage (%)	GHG emission (kg $CO_{2eq.}$ ha^{-1})	Percentage (%)
Diesel	78.2	9.7	738.2	2.1
Chemical fertilizer				
N	281.3	35	877.7	2.5
P_2O_5	40	5	405.1	1.2
K_2O	48.8	6.1	210	0.6
Biocide	196.7	24.5	201.7	0.6
Machinery	79.6	10	82	0.2
Electricity	78.8	9.7	18962.1	54
Natural gas	–	–	13606.7	38.8
Total emission	803.4	100	35083.5	100

3.2. Greenhouse gases emission

The conversion factors shown in Table 2 were applied to calculate the GHG emissions. The results of emissions based on two different cultivation systems are presented in the Table 5. As can be seen the amount of total GHG emission in GH production was significantly higher than that in OF production. The value of total GHG emission of OF strawberry production was estimated at 803.4 kg CO_{2eq} ha^{-1} while its counterpart in GH production was 35,083.5 kg CO_{2eq} ha^{-1}. To review the literature revealed that the amount of GHGs emitted from strawberry production has not been studied yet, so the results were compared to findings about other crops. The total CO_2 emission of cucumber production was calculated as 45177.3 kg CO_2eq ha^{-1} in Esfehan province of Iran [27]. Pishgar-Komleh et al. [13] reported that the total value of GHG emission of potato production was calculated as 992.88 kg CO_{2eq} ha^{-1}. In another study on Effects of alternative management practices on the economics, energy and GHG emissions of a wheat–pea cropping system, Khakbazan et al. [28] showed that the total emission can be ranged from 410 kg CO_{2eq} ha^{-1} to 1130 kg CO_{2eq} ha^{-1} based on fertilizer rate, location and seeding system.

The results revealed that the most value of emission in OF production was related to nitrogen fertilizer with amount of 281.3 kg CO_{2eq} ha^{-1} and followed by biocide and machinery. Electricity was the major contributor to GHG emission in GH production and the second rank was held by natural gas with a portion of 38.8%.

Based on the results the GHG ratio was calculated as 483.8 kg CO_{2eq} t^{-1} and 146.7 kg CO_{2eq} t^{-1} for GH and OF production, respectively. It means that on average the production of one ton strawberry in greenhouses is responsible for 483.8 kg CO_2 emission which is 3.29 times more than that in open fields. By increasing the demand of countries for fresh agricultural produce, application of intensive cropping systems such as greenhouses is inevitable. Hence, improvement of energy use efficiency in greenhouse production can be the best way for reducing the GHG ratio.

3.3. Benchmarking

As it was previously elaborated, benchmark ranking method helps to find the most appropriate DMUs relative to others in the group. Table 6 presents the performance ranking of the 33 DMUs using this approach. As can be observed in Table 6, the GH12 appeared in the benchmark referent set of most inefficient DMUs (as highlighted in the column of benchmarks). Accordingly, GH12 with 13 repetitions (see Table 6; Frequency in referent set) was given the top ranking. It means that this greenhouse is not only efficient but is also close to input–output levels of the most inefficient units in the group and it was followed by GH06 and GH01 with 10 and 9 repetitions, respectively. The most important conclusion that can be drawn from these results is that, inefficient DMUs can enhance their energy use efficiency by following the best practices of the efficiency DMUs. In other words an inefficient DMU can be efficient if it follows a composite DMU instead of using a single DMU as a benchmark. For example, in the case of GH04, this unit should follow the practices of GH07, 11 and 12 as composite DMU which means that GH04 is close to the efficient frontier segment formed by these efficient DMUs.

To clarify benchmarking, consider greenhouse number 4 (See GH04 in Table 6). TE of GH04 was calculated to be 0.99. To improve efficiency score of GH04, it should be changed to a composite DMU. The composite DMU that represents the best practice or reference composite benchmark DMU is formed by the combination of GH07, GH11, and GH12. The number in the parentheses is called intensity vector indicating that the inputs and output of selected inefficient DMU (GH04) is closer to GH07 compared to other three greenhouses. Using intensity vectors and benchmarked greenhouses the optimum amount of energy for GH04 can be worked out.

Table 6
Results of technical efficiency analysis.

DMU	TE score	Frequency in referent set	Benchmarks
GH01	1.00	9	
GH02	1.00	2	
GH03	1.00	6	
GH04	0.99		7 (0.53) 11 (0.05) **12 (0.15)**
GH05	1.00	1	
GH06	1.00	10	
GH07	1.00	8	
GH08	1.00	8	
GH09	1.00	1	
GH10	1.00	0	
GH11	1.00	5	
GH12	1.00	13	
GH13	0.91		1 (0.50) 8 (0.30)
GH14	0.51		6 (0.34) 11 (0.05) **12 (0.29)** 17 (0.01)
GH15	0.83		3 (0.10) 6 (0.27) 7 (0.13) 8 (0.12) 11 (0.02) **12 (0.05)**
GH16	0.84		1 (0.06) 3 (0.02) 7 (0.20) 8 (0.38) **12 (0.26)**
GH17	1.00	4	
GH18	0.55		2 (0.02) 3 (0.55) 6 (0.03)
GH19	1.00	3	
GH20	0.95		2 (0.48) 3 (0.07) 5 (0.04) 6 (0.03) 8 (0.13)
GH21	0.71		1 (0.54) 3 (0.06) 19 (0.13)
GH22	0.54		6 (0.02) 7 (0.26) **12 (0.29)** 17 (0.10)
GH23	0.68		6 (0.34) 7 (0.33) **12 (0.19)**
GH24	0.63		7 (0.18) **12 (0.43)** 17 (0.07)
GH25	1.00	2	
GH26	0.56		1 (0.22) 8 (0.04) **12 (0.38)**
GH27	0.76		1 (0.12) 6 (0.37) 8 (0.16) **12 (0.03)**
GH28	0.78		1 (0.08) 6 (0.39) 7 (0.22)
GH29	0.79		1 (0.25) **12 (0.17)** 25 (0.33)
GH30	0.73		6 (0.02) 7 (0.08) 9 (0.21) 11 (0.41) **12 (0.09)** 17 (0.03)
GH31	0.71		1 (0.04) 6 (0.00) 8 (0.20) **12 (0.19)** 19 (0.10) 25 (0.13)
GH32	0.89		1 (0.22) 3 (0.11) 8 (0.52) 19 (0.04)
GH33	0.58		11 (0.39) **12 (0.19)**

3.4. Improvement of energy use efficiency in GH strawberry production

According to the obtained results from BCC model, 19 greenhouses (58%) out of 33 gained the efficiency score of one (Fig. 2). On the other hand the remaining 14 DMUs which gained efficiency scores less than one were comparatively inefficient. Among inefficient greenhouses 7 DMUs (21%) were in the range of 0.9 and 0.99. CCR model results demonstrated that from the total of 33 DMUs considered for the present study, 14 greenhouses had technical efficiency score of one; while, 19 DMUs obtained efficiency score less than one and these 19 greenhouses were relatively inefficient. Inefficient DMUs had efficiency score between 0.5 and 0.99.

Table 7 summarizes the efficiency scores of all greenhouses. As can be seen the average values of PTE, TE and SE were calculated as 0.95, 0.85 and 0.89, respectively. The values of PTE less than one means that the target DMU is using more energy than is required [19]. The average TE (0.85) indicates that these DMUs can produce the same level of output with application of 85% of current energy consumption and 15% of energy from different sources can be saved. The mean value of SEs (0.89) shows that there is ample scope for improving the operating practices to enhance the energy use efficiency without any change in technological practices. In other words, 15% of energy from different sources can be saved if inefficient DMUs follow the agricultural practices of efficient ones. Based on the literature, the technical efficiency scores of 0.82 for greenhouse cucumber [10], 0.82 for greenhouse tomato [29], and 0.68 for greenhouse rose producers [30] were reported.

The BCC model includes both IRS and DRS, while a NIRS model gives DRS. To determine whether a DMU has IRS or DRS an additional test is required. The values of TE for both BCC and NIRS were

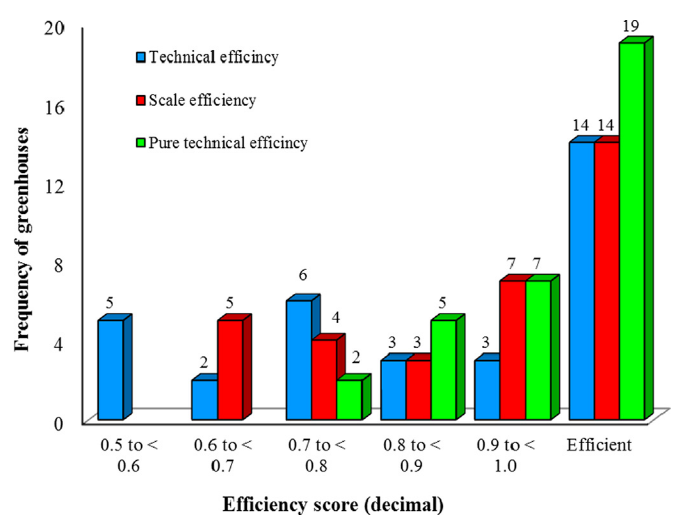

Fig. 2. Efficiency score distribution of GH strawberry producers in Iran.

Table 7
Technical and scale efficiencies and returns to scale.

DMU	Technical efficiency			Scale efficiency (CCR/BCC)	Return to scale
	CCR	BCC	NIRS		
1	1.00	1.00	1.00	1.00	Constant
2	1.00	1.00	1.00	1.00	Constant
3	1.00	1.00	1.00	1.00	Constant
4	0.99	1.00	0.99	0.99	Increasing
5	1.00	1.00	1.00	1.00	Constant
6	1.00	1.00	1.00	1.00	Constant
7	1.00	1.00	1.00	1.00	Constant
8	1.00	1.00	1.00	1.00	Constant
9	1.00	1.00	1.00	1.00	Constant
10	1.00	1.00	1.00	1.00	Constant
11	1.00	1.00	1.00	1.00	Constant
12	1.00	1.00	1.00	1.00	Constant
13	0.91	1.00	0.91	0.91	Increasing
14	0.51	0.71	0.51	0.73	Increasing
15	0.83	1.00	0.83	0.83	Increasing
16	0.84	0.89	0.84	0.94	Increasing
17	1.00	1.00	1.00	1.00	Constant
18	0.55	0.89	0.55	0.61	Increasing
19	1.00	1.00	1.00	1.00	Constant
20	0.95	1.00	0.95	0.95	Increasing
21	0.71	0.90	0.71	0.79	Increasing
22	0.54	0.80	0.54	0.68	Increasing
23	0.68	0.72	0.68	0.95	Increasing
24	0.63	0.92	0.63	0.68	Increasing
25	1.00	1.00	1.00	1.00	Constant
26	0.56	0.86	0.56	0.65	Increasing
27	0.76	1.00	0.76	0.76	Increasing
28	0.78	0.95	0.78	0.82	Increasing
29	0.79	0.93	0.79	0.86	Increasing
30	0.73	0.81	0.73	0.91	Increasing
31	0.71	0.99	0.71	0.71	Increasing
32	0.89	0.93	0.89	0.96	Increasing
33	0.58	0.91	0.58	0.64	Increasing
Average	**0.85**	**0.95**	**0.85**	**0.89**	
Max	1.00	1.00	1.00	1.00	
Min	0.51	0.71	0.51	0.61	
SD	0.17	0.08	0.17	0.13	

Table 8
Energy saving (MJ ha^{-1}) from different sources if recommendation of study are followed.

Input	Target use (MJ ha^{-1})	Energy saving (MJ ha^{-1})	Contribution of input to savings (%)
1. Human labor	24320	814.3	0.3
2. Chemical fertilizer			
N	39743.5	4911.0	1.8
P_2O_5	22425.6	2771.1	1
K_2O	10896.9	810.6	0.3
Micro	21041.5	1467.6	0.5
3. FYM	15819.6	3635.0	1.3
4. Biocides	4534.1	987.8	0.4
5. Machinery	1010.4	144.0	0.1
6. Water for irrigation	18238.9	6114.4	2.2
7. Diesel fuel	10054.5	2730.8	1
8. Electricity	341134.6	30933.8	11.3
9. Natural gas	574570.3	217822.6	79.7
Total input energy (MJ/ha)	1083789.8	273902.8	20.2

calculated and the obtained values were compared. The same values of TE for NIRS and BCC models show that the DMU has DRS, while the different values imply that the farm has IRS [3]. The last column of Table 7 indicates the results of RTS for some selected DMUs. These results revealed that 15 greenhouses (based on CCR model) had CRS while 18 DMUs were found to be operating at IRS. Therefore a proportionate increase in all inputs leads to more proportionate increase in outputs. The information on whether a farmer operates at IRS, CRS or DRS is particularly helpful in indicating the potential redistribution of resources between the farmers, and thus, enables them to achieve to the higher yield value [31].

Table 8 summarizes the target energy use and energy saving for all energy sources. The results revealed that the total input energy can be reduced to 1,083,789.8 MJ ha^{-1}, while the current yield will not change. On the other hand, it means that 273,902.8 MJ ha^{-1} can be saved if all inefficient DMUs improved their conditions from energy use point of view and try to close themselves to efficient frontier segment formed by efficient DMUs. The last column of Table 8 presents the share of different sources in the total energy saving. It is evident that the maximum contribution to the total energy savings was 79.7% and it belonged to natural gas, followed by electricity (11.3%), chemical fertilizers (3.6%) and water (2.2%).

To help inefficient farmers to close themselves to the efficient ones, it necessitates advising them to reduce the input energy levels to the target values while no changes in the output level be made. Table 9 displays TE, actual energy consumption in inefficient DMUs and optimum energy requirement from different sources. By improvement of energy use efficiency based on the optimum energy consumption presented in Table 9, the energy indices will be improved. Based on the results if the performance of inefficient farms is raised, the energy ratio will be enhanced to the value of 0.13. Additionally, energy productivity, specific energy and net energy can be improved to the values of 0.07 kg MJ^{-1}, 15.56 MJ kg^{-1} and −946,017.41 MJ ha^{-1} if recommendation of the present study are followed.

3.5. Impact of energy use efficiency on GHG emission

As it was mentioned above the energy consumption can be reduced by improving some agricultural practices in inefficient DMUs. Subsequently, the emission of GHG due to consumption of energy inputs can be decreased in the studied region. As can be seen in Table 10, the total GHG emission can be reduced to the value of 29309.1 kg CO_{2eq} ha^{-1}. In other words by improvement of energy use efficiency 5,774.4 kg CO_{2eq} ha^{-1} can be reduced. The most reduction was observed in natural gas by 64.8% of the total reduced emission followed by electricity (27.3%).

Based on the obtained results it was revealed that the amount of GHG emission of greenhouse strawberry production is extremely high. Also, considering that off-season greenhouse production is necessary due to huge demand for fresh produce, finding appropriate agricultural management especially those that can reduce energy consumption and its environmental consequences are crucial. The results of the present study revealed that OF strawberry production due to less energy consumption and GHG emission is more environmentally friendly than GH production. However, to satisfy the high demand for this crop, GH strawberry production cannot be neglected.

The following methods and tips can help greenhouse holders to improve their energy use efficiency. Improvement of heating systems, applying more efficient electrical pumps for irrigation systems, supplying electricity from non-fossil resources and providing the possibility of storage and application of rainfall in the studied region are highly recommended. Also, the structure of these curved roof greenhouses is not appropriate for strawberry production. Greenhouse strawberries are cultivated in the soil and they grow horizontally, so the height of the greenhouses specialized in strawberry cultivation can be decreased which helps farmers to use less energy to warm greenhouses. Most of the energy consumed in a greenhouse is used for heating, and most heating (around 80 percent) occurs at night. Deploying a retractable shade/energy curtain at night can significantly reduce heat loss by providing another insulating layer. Moreover the nylon which was mostly used to cover greenhouses was not appropriate for winter season and they should be changed or thicker nylon or an extra layer should be

Table 9
The percentages in energy savings of inefficient growers (based on CCR model).

DMU	TE	Actual energy use (GJ/ha)									Optimal energy requirement (GJ/ha)								
		Labor	Chemical fertilizer	FYM	Diesel fuel	Elc.	NG	Bio	Mach.	Water for irr.	Lab.	Chemical fertilizer	FYM	Diesel fuel	Elc.	NG	Bio.	Mach.	Water for irr.
4	0.99	27.9	84.1	30.0	6.4	393.7	396.0	6.6	0.7	9.7	16.5	68.0	9.2	6.4	346.4	244.9	3.9	0.6	9.7
13	0.91	41.8	83.1	18.0	9.6	120.8	742.5	4.0	1.7	38.8	24.9	75.3	10.3	9.6	120.8	510.4	2.4	1.0	22.2
14	0.51	26.8	135.0	18.0	22.3	626.3	767.3	6.0	1.5	21.4	26.8	128.9	16.5	16.8	540.1	754.5	5.7	1.5	21.4
15	0.83	19.5	78.1	21.0	10.2	331.1	371.3	3.9	0.9	24.5	19.5	75.8	10.9	7.2	331.1	371.3	3.8	0.9	12.3
16	0.84	27.9	117.1	25.5	7.6	322.1	495.0	6.2	1.2	22.4	23.9	96.3	13.9	7.6	322.1	495.0	4.3	0.8	17.1
18	0.55	31.4	87.7	10.5	22.3	626.3	767.3	8.9	1.5	21.4	30.7	80.3	10.5	16.2	575.0	617.1	7.6	1.5	21.4
20	0.95	18.8	69.4	15.0	8.3	334.6	519.8	3.8	1.0	8.7	18.3	53.1	15.0	8.3	297.8	373.7	3.5	1.0	8.0
21	0.71	41.8	143.3	22.5	28.7	161.1	1361.3	4.1	1.6	68.3	32.5	106.6	16.0	18.1	161.1	853.9	3.6	1.6	40.2
22	0.54	23.7	135.0	18.0	10.2	581.6	519.8	6.8	1.5	56.1	23.7	129.0	17.2	10.2	525.9	519.7	6.1	1.2	36.5
23	0.68	30.7	126.4	22.5	10.2	581.6	519.8	6.0	1.5	56.1	28.6	122.6	16.9	9.9	538.5	519.8	5.8	1.4	28.3
24	0.63	19.5	129.7	19.5	10.2	581.6	519.8	7.9	1.5	56.1	19.5	112.1	16.0	9.4	449.0	519.8	5.7	1.0	33.9
26	0.56	25.1	131.1	27.0	15.9	232.6	660.0	6.8	0.9	56.1	24.8	112.6	19.4	13.6	232.6	328.4	5.0	0.9	41.9
27	0.76	20.9	158.8	21.0	10.2	275.1	470.3	3.1	1.1	20.4	20.9	100.9	12.1	7.9	261.2	454.9	3.1	1.1	13.7
28	0.78	25.1	135.0	24.0	8.3	349.2	371.3	5.1	1.3	10.2	22.2	97.5	12.9	7.7	349.2	371.3	4.2	1.2	10.2
29	0.79	30.1	126.4	30.0	19.1	179.0	990.0	6.3	0.9	51.0	25.7	102.6	17.3	14.4	179.0	729.5	5.2	0.9	28.3
30	0.73	25.1	129.7	24.0	19.1	492.1	693.0	8.9	0.9	17.3	25.1	103.1	18.3	16.1	492.1	693.0	7.5	0.9	17.3
31	0.71	20.9	112.7	30.0	15.9	223.7	792.0	5.1	0.9	15.3	20.9	95.5	17.7	10.9	223.7	648.4	4.3	0.9	15.3
32	0.89	30.7	110.4	27.0	15.9	223.7	792.0	8.9	0.9	15.3	25.0	83.8	12.0	8.8	223.7	532.3	3.7	0.9	15.3
33	0.58	19.5	89.9	24.0	22.3	626.3	767.3	6.8	1.5	21.4	19.5	78.9	17.0	18.3	504.7	709.6	6.2	1.1	20.6

Table 10
Target GHG emission of inputs.

Item	Target emission (kg $CO_{2eq.}$ ha^{-1})	Emission reduction (kg $CO_{2eq.}$ ha^{-1})	Percentage (%)
1. Diesel	580.6	157.7	2.7
2. Chemical fertilizer			
N	781.2	96.5	1.7
P_2O_5	360.5	44.6	0.8
K_2O	195.5	14.5	0.3
6. Biocide	138.8	62.9	1.1
3. Machinery	0.7	81.3	1.4
4. Electricity	17385.6	1576.5	27.3
5. Natural gas	9866.4	3740.4	64.8
Total emission	29309.1	5774.4	

employed in order to minimize the waste of heat which is squandered due to conduction. Most greenhouse holders are still not taking advantage of infrared (IR) plastic film on their greenhouses which avoid heat provided by the heating system is lost by conduction, convection and radiation. Looking for gaps near fans, pads, doors or in the greenhouse roof can help farmers to improve insulation. Application of high level technology of ventilation as well as applying thermostat controllers in suitable places of greenhouses can reduce high consumption of natural gas and electricity and consequently the environmental burdens of greenhouse strawberry cultivation can be reduced. Application of modern technologies can help greenhouse holders to achieve optimum application of energy from different sources. Several types of modern greenhouse heating systems can be installed. Modern solid built hot water boilers with efficient gas burners, in combination with an adequately designed pump and pipe systems guarantee low energy consumption, reliable operation and a minimum of maintenance. Sub-distribution manifold is a new technology in a greenhouse for accurate computer controlled heat distribution and temperature control.

4. Conclusions

In this study the input and output energies in greenhouse and open field strawberry production were investigated and GHG emission of two production systems were compared. 70 open field farms and 33 greenhouses were randomly selected for data collection. Data envelopment analysis was used to determine the efficiency and inefficiency of GH producers. The total average input and output energies were calculated as 35092.4 MJ ha^{-1} and 10405.9 MJ ha^{-1} for OF production and 1356932.8 MJ ha^{-1} and 137772.4 MJ ha^{-1} for GH strawberry production. Among the input energies in GH production natural gas and electricity had the largest share with 58.4% and 27.4%, respectively. The total GHG emission was assessed as 803.4 kg CO_{2eq} ha^{-1} and 35083.5 kg CO_{2eq} ha^{-1} for OF and GH production, respectively. According to the results 14 greenhouses were technically efficient while based on the BCC model 19 growers were identified as efficient. Comparison between present and target energy use showed that 273902.8 MJ ha^{-1} can be saved if all inefficient DMUs use energy according to the recommendations of this study. The maximum contribution to the total energy saving is 79.7% which belongs to the natural gas, followed by electricity (11.3%). Based on the results it was concluded that, by energy optimization the total GHG emission can be reduced to the value of 29309.1 kg CO_{2eq} ha^{-1}.

Acknowledgment

The financial support provided by the University of Tehran, Iran, is duly acknowledged.

References

[1] Romero-Gámez M, Suárez-Rey EM, Antón A, Castilla N, Soriano T. Environmental impact of screenhouse and open-field cultivation using a life cycle analysis: the case study of green bean production. Journal of Cleaner Production 2012;28:63–9.
[2] Singh RD, Tiwari GN. Energy conservation in the greenhouse system: a steady state analysis. Energy 2010;35:2367–73.
[3] Omid M, Ghojabeige F, Delshad M, Ahmadi H. Energy use pattern and benchmarking of selected greenhouses in Iran using data envelopment analysis. Energy Conversion and Management 2011;52:153–62.
[4] Banaeian N, Omid M, Ahmadi H. Energy and economic analysis of greenhouse strawberry production in Tehran province of Iran. Energy Conversion and Management 2011;52:1020–5.
[5] Tabatabaie MH, Rafiee S, Keyhani A. Energy consumption flow and econometric models of two plum cultivars productions in Tehran province of Iran. Energy 2012;44:211–6.
[6] Nemecek T, Dubois D, Huguenin-Elie O, Gaillard G. Life cycle assessment of Swiss farming systems: I. Integerated and organic farming. Agriculture Systems 2011;104:217–32.

[7] Mousavi-Avval SH, Mohammadi A, Rafiee S, Tabatabaeefar A. Assessing the technical efficiency of energy use in different barberry production systems. Journal of Cleaner Production 2012;27:126–32.
[8] Pahlavan R, Omid M, Akram A. Energy input–output analysis and application of artificial neural networks for predicting greenhouse basil production. Energy 2012;37:171–6.
[9] Rafiee S, Mousavi Avval SH, Mohammadi A. Modeling and sensitivity analysis of energy inputs for apple production in Iran. Energy 2010;35:3301–6.
[10] Heidari MD, Omid M, Mohammadi A. Measuring productive efficiency of horticultural greenhouses in Iran: a data envelopment analysis approach. Expert Systems with Applications 2012;39:1040–5.
[11] Canakci M, Akinci I. Energy use pattern analyses of greenhouse vegetable production. Energy 2006;31:1243–56.
[12] Ozkan B, Akcaoz H, Karadeniz F. Energy requirement and economic analysis of citrus production in Turkey. Energy Conversion and Management 2004;45:1821–30.
[13] Pishgar-Komleh SH, Ghahderijani M, Sefeedpari P. Energy consumption and CO_2 emissions analysis of potato production based on different farm size levels in Iran. Journal of Cleaner Production 2012;33:183–91.
[14] Kitani O. Energy and Biomass Engineering in: St. Joseph, M.A. (Ed.). CIGR Handbook of Agricultural Engineering 1999. p. 330.
[15] Ramedani Z, Omid M, Fahimi F, Mirzaee F. A comparative study on energy inputs and yield of canola production under different environmental conditions. Journal of Agricultural Technology 2012;8:811–24.
[16] Mohammadshirazi A, Akram A, Rafiee S, Mousavi Avval SH, Bagheri Kalhor E. An analysis of energy use and relation between energy inputs and yield in tangerine production. Renewable and Sustainable Energy Reviews 2012;16:4515–21.
[17] Lal R. Carbon emission from farm operations. Environment International 2004;30:981–90.
[18] Cooper W, Seiford LM, Tone K. Data envelopment analysis, a comprehensive text with models, applications, references and DEA-solver software. Massachusetts, USA: Kluwer Academic Publishers; 2004.
[19] Charnes A, Cooper WW, Rhodes E. Measuring the efficiency of decisionmaking units. European Journal of Operational Research 1978;2:429–44.
[20] Liu CH, Lin SJ, Lewis C. Evaluation of thermal power plant operational performance in Taiwan by data envelopment analysis. Energy Policy 2010;38:1049–58.
[21] Banker RD, Charnes A, Cooper WW. Some models for estimating technical and scale inefficiencies in data envelopment analysis. Managment Science 1984;30:1078–92.
[22] Malana NM, Malano HM. Benchmarking productive efficiency of selected wheat areas in Pakistan and India – data envelopment analysis. Irrigation and Drainage 2006;55:383–94.
[23] Sarıca K, Or I. Efficiency assessment of Turkish power plants using data envelopment analysis. Energy 2007;32:1484–99.
[24] Safa M, Samarasinghe S. Determination and modelling of energy consumption in wheat production using neural networks: "A case study in Canterbury province, New Zealand". Energy 2011;36:5140–7.
[25] Mousavi-Avval SH, Rafiee S, Jafari A, Mohammadi A. Energy flow modeling and sensitivity analysis of inputs for canola production in Iran. Journal of Cleaner Production 2011;19:1464–70.
[26] Hamedani SR, Shabani Z, Rafiee S. Energy inputs and crop yield relationship in potato production in Hamadan province of Iran. Energy 2011;36:2367–71.
[27] Khoshnevisan B, Rafiee S, Omid M, Mousazadeh H. Reduction of CO_2 emission by improving energy use efficiency of greenhouse cucumber production using DEA approach. Energy 2013;55:676–82.
[28] Khakbazan M, Mohr RM, Derksen DA, Monreal MA, Grant CA, Zentner RP, et al. Effects of alternative management practices on the economics, energy and GHG emissions of a wheat–pea cropping system in the Canadian prairies. Soil and Tillage Research 2009;104:30–8.
[29] Pahlavan R, Omid M, Akram A. Energy use efficiency in greenhouse tomato production in Iran. Energy 2011;36:6714–9.
[30] Pahlavan R, Omid M, Rafiee S, Mousavi-Avval SH. Optimization of energy consumption for rose production in Iran. Energy for Sustainable Development 2012;16:236–41.
[31] Chauhan NS, Mohapatra PKJ, Pandey KP. Improving energy productivity in paddy production through benchmarking – an application of data envelopment analysis. Energy Conversion and Management 2006;47:1063–85.